Search for dark sector at BESIII

Yu Zhang (南华大学)

for the BESIII Collaboration

yuzhang@usc.edu.cn

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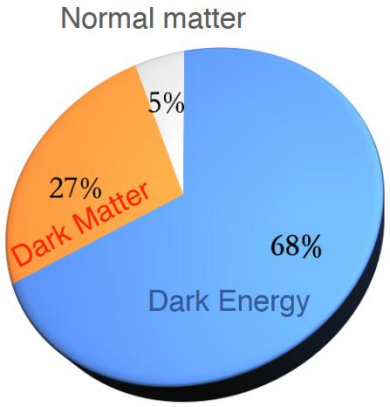
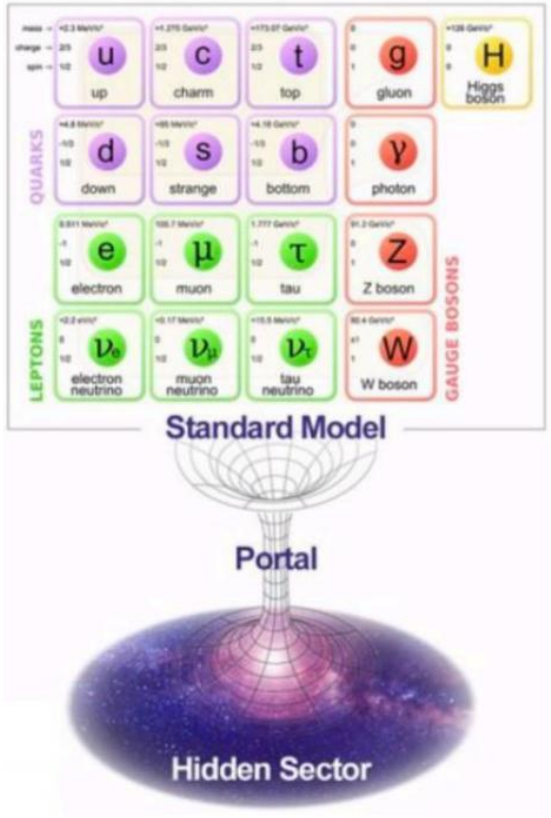
Outline

- Introduction
- BESIII experiment
- Search for muonphilic vector/scalar
- Search for axion-like particles
- Search for dark photons
- Summary

Dark matter interacting with SM



- Amounts 27% of the total matter density of the universe
- Not interact with strong and electromagnetic interactions
- Explain the features of astrophysical observations



$$\mathcal{L} \supset \begin{cases} -\frac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H, & \text{Higgs portal} \\ y_n L H N, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, & \text{axion portal} \end{cases}$$

A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

Sterile neutrino

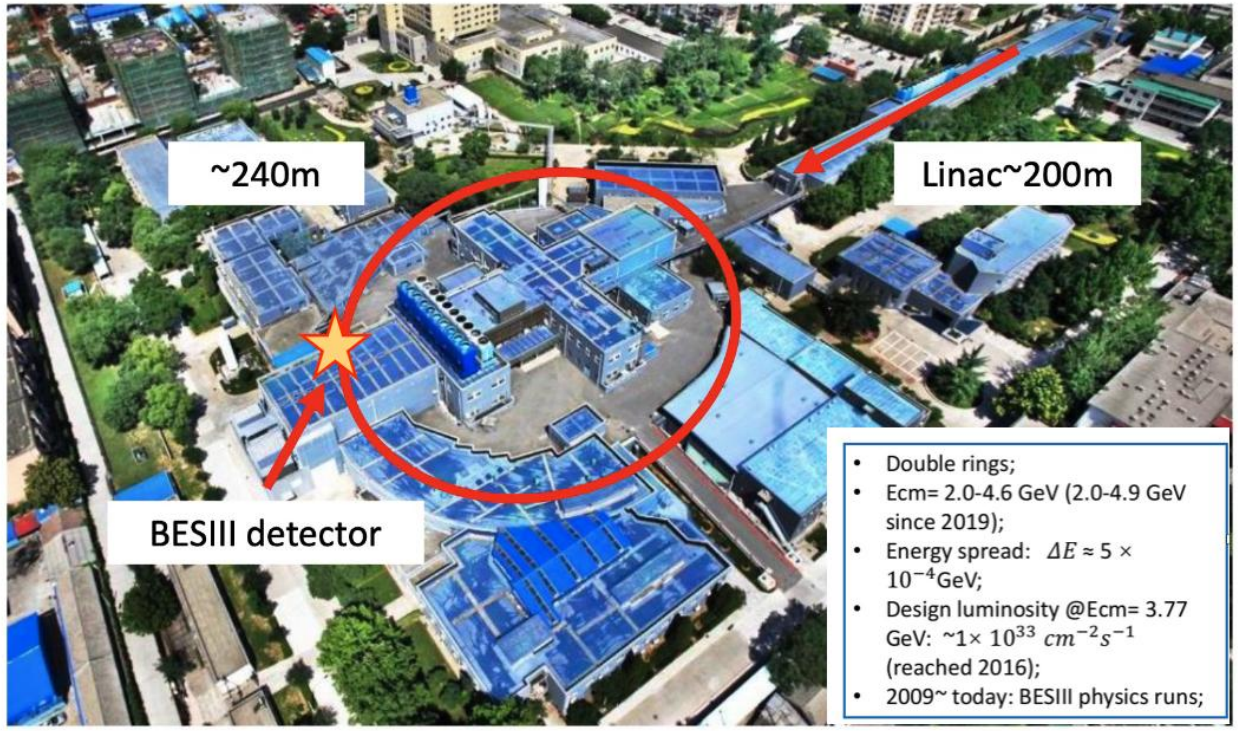
Axion, coupling to DM

arxiv:1311.0029

- Dark matter has not seen yet in particle physics experiments
- One of the simplest models is "DM hidden sector" that allows the coupling between DM and SM particles via the so called "portals"
- "Portal" interactions are accessible by high intensity e+e- collider experiments, such as BESIII experiment, if their masses are ~GeV

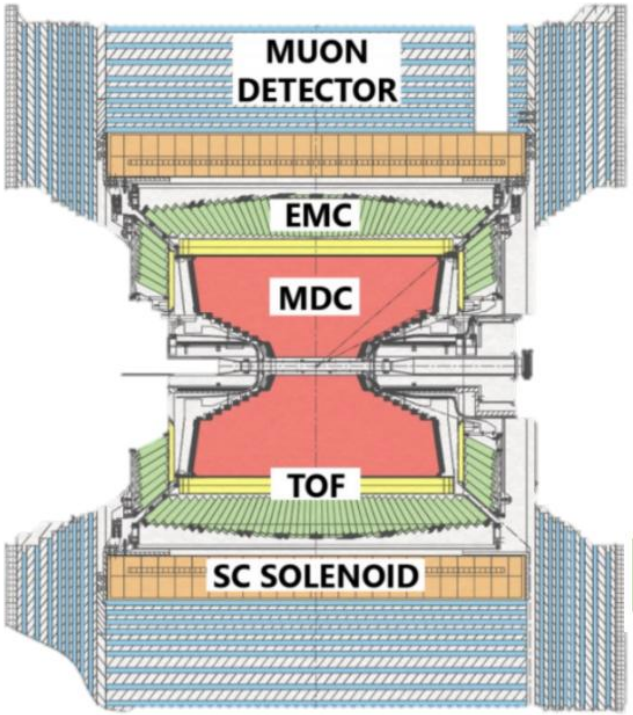
BESIII experiment

Beijing Electron–Positron Collider II



- Double rings;
- Ecm= 2.0-4.6 GeV (2.0-4.9 GeV since 2019);
- Energy spread: $\Delta E \approx 5 \times 10^{-4}$GeV;
- Design luminosity @Ecm= 3.77 GeV: ~$1\times 10^{33}\ cm^{-2}s^{-1}$ (reached 2016);
- 2009~ today: BESIII physics runs;

Beijing Spectrometer III



Main Drift Chamber
σ_p/p <0.5% (@1GeV) (1T)
σ_{xy} ~120 μm
dE/dx~6%

Time Of Flight
$\sigma_t < 68ps$(barrel)
$\sigma_t <$ 60ps (endcap)

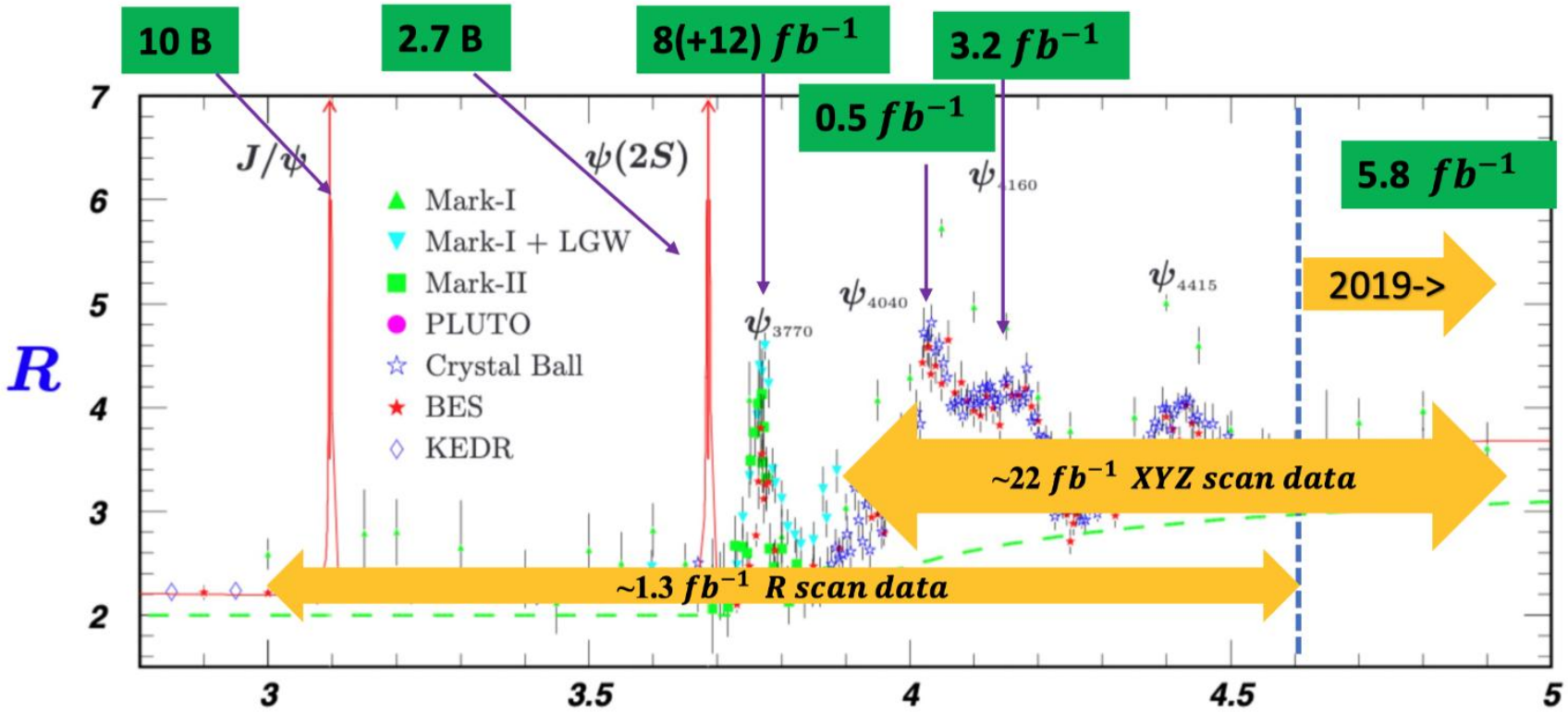
Electromagnetic Calorimeter
σ_E/E<2.5%(5%) @1GeV
σ_{xy}~6mm (@1GeV)

Muon Counter
$\sigma_{\text{spatial}} < 2cm$

A symmetric e^+e^- collider running at tau-charm (2-5 GeV) region

BESIII data sets

- World's largest data samples in tau-charm region
- 10 billion J/ψ, 2.7 billion $\psi(3686)$ and 20 fb^{-1} $\psi(3770)$ on threshold



- Charmonium
- XYZs
- Charm physics
- Light hadron
- Tau physics
- New physics

Exotic particles search at BESIII

Dark matter portals

Axion-like particles (ALP)

With ψ(2S) data set
- PLB 838 (2023) 137698

With J/ψ data set
- PRD 110 (2024) L031101

Invisible decays

Invisible muon philic scalar/vector
- PRD 109 (2024) L031102

Σ^+ →proton+invisible
- PLB 852 (2024) 138614

Λ baryon
- PRD 105 (2022) L071102

ω/ϕ mesons
- PRD 98 (2018) 032001

η/η' mesons
- PRD 87 (2013) 012009

Light CP-odd higgs boson

Visible decay
- PRD 105 (2022) 012008
- PRD 93 (2016) 052005
- PRD 85 (2012) 092012

Invisible decay
- PRD 101 (2020) 112005

Dark photon

ISR process
- PLB 839 (2023) 137785 (invisible)
- PLB 774 (2017) 252 (visible)

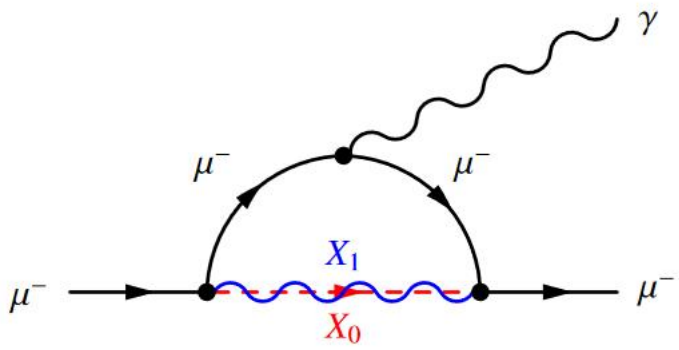
With J/ψ data set
- PRD 99 (2019) 012013
- PRD 99 (2019) 012006
- PRD 102 (2020) 052005

Massless dark photon
- PRD 106 (2022) 072008

Heavy Majorana neutrino

- PRD 99 (2019) 112002

Muonphilic scalar/vector $X_{0/1}$

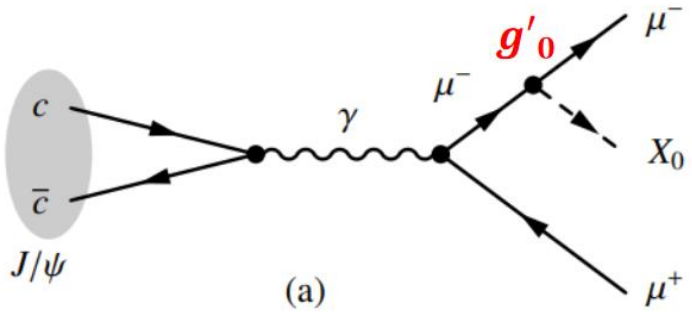


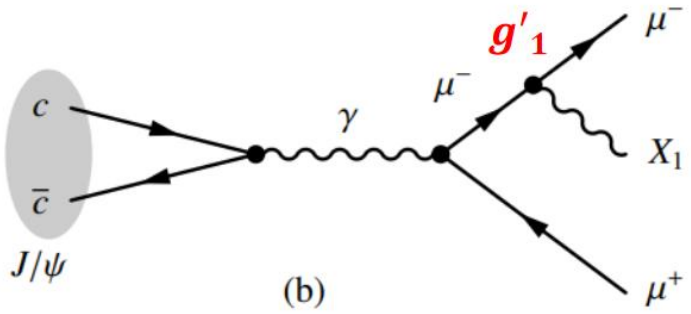
JHEP 10 (2020) 207

- Proposed as a explanation to the $(g-2)_\mu$ anomaly
- A minimal extention of $U(1)$ group is added to the SM
- $U(1)_{L_\mu - L_\tau}$ model:

  a massive scalar X_0 or vector X_1 boson couples only with the 2nd and 3rd generation leptons $\mathcal{L}_\mu^{\text{scalar}} = -g_0 X_0 \bar{\mu}\mu$, $\mathcal{L}_\mu^{\text{vector}} = -g_1 X_1 \bar{\mu}\gamma\mu$

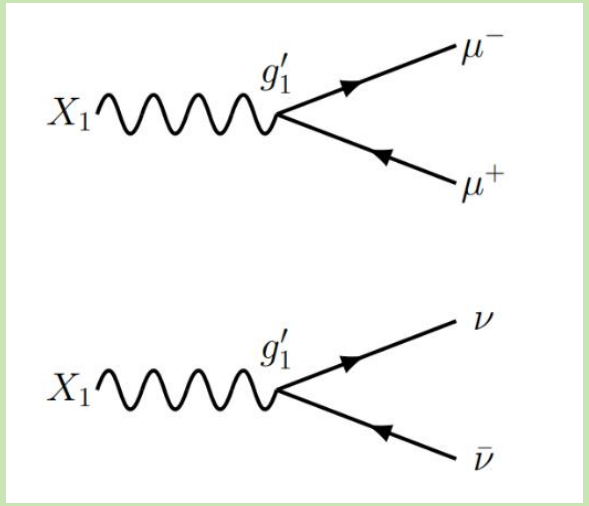
- **Can be studied with J/$\psi \to \mu^+\mu^- X_{0/1}$**





Three model scenarios

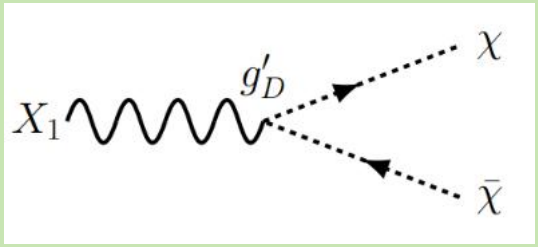
"Vanilla" $L_\mu - L_\tau$ model



X_1 only couples to SM particles

$BF(X_1 \to \nu\nu) \sim (33 - 100)\%$

Invisible $L_\mu - L_\tau$ model



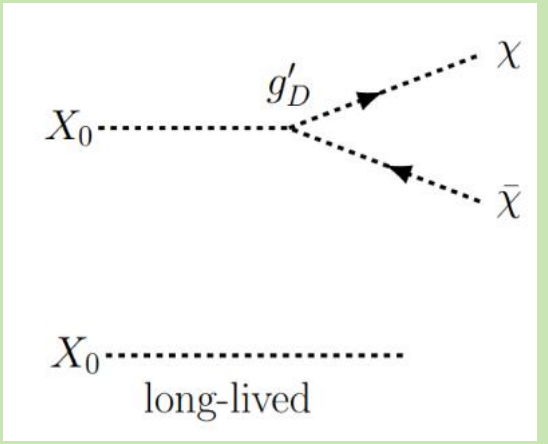
Dark matter particle χ couples to X_1 with strength g'_D

$m_\chi < m_{X_1}/2$

$g'_D \gg g'_1$

$BF(X_1 \to \chi\bar{\chi}) \sim 100\%$

Scalar $U(1)$ model



Dark matter particle χ couples to X_0 with strength g'_D

X_0 is long lived or only decays to invisible final states

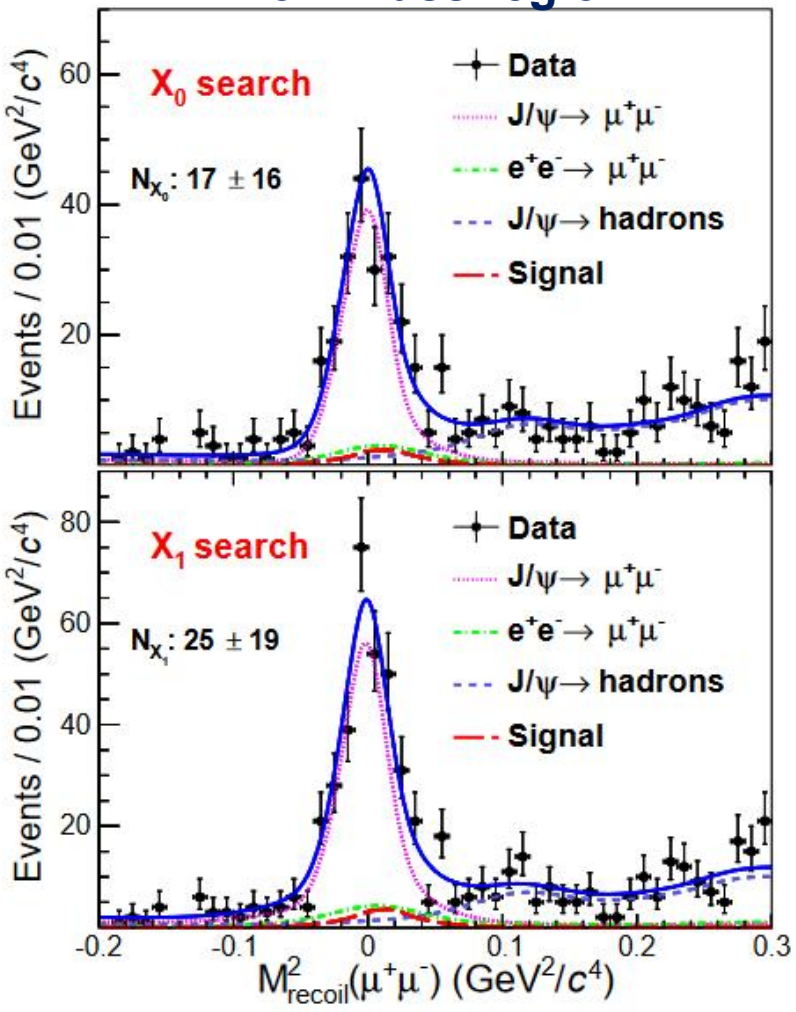
Search for $J/\psi \to \mu^+\mu^- X_{0/1}$

Search for $X_{0/1}$ in the mass region 1 MeV - 1 GeV

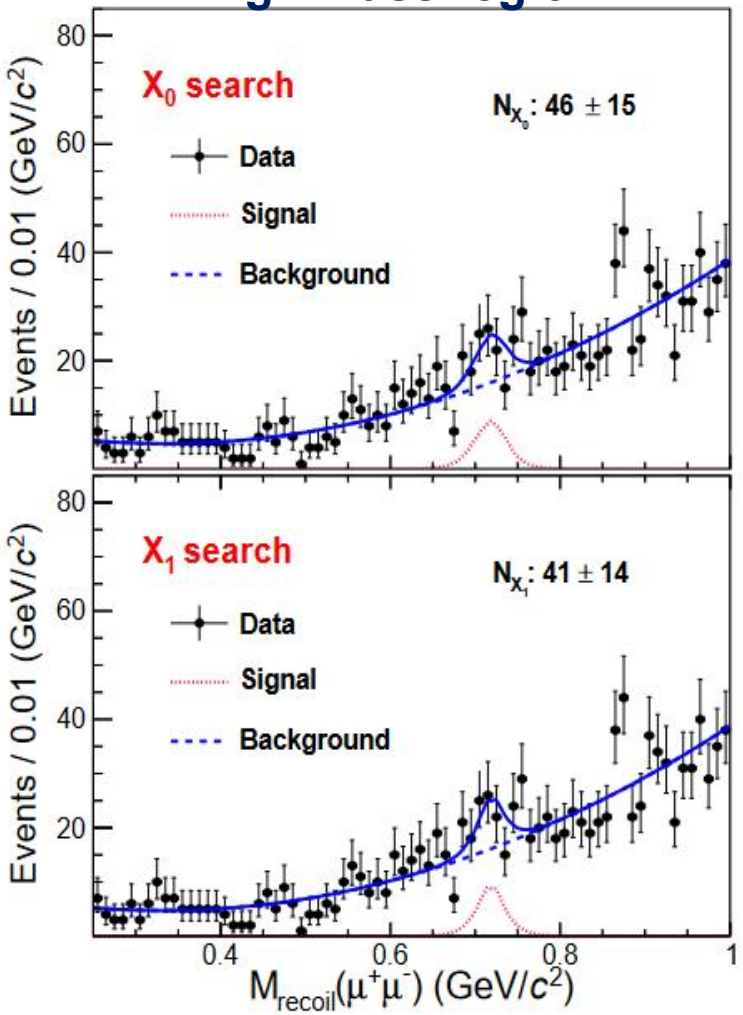
No evidence for the signals of $X_{0/1}$ invisible decay

Maximum local significance is 2.5σ at 0.72 GeV/c^2

Low mass region



High mass region

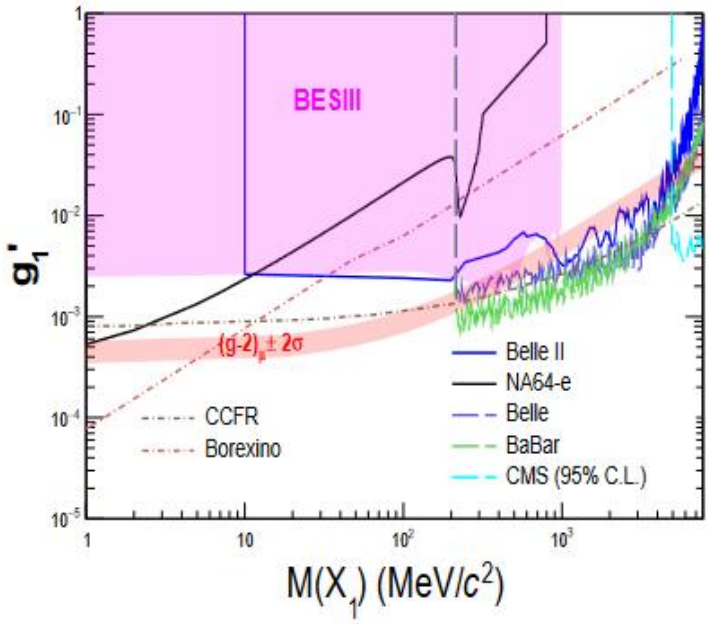


PRD (2024) 109, L031102

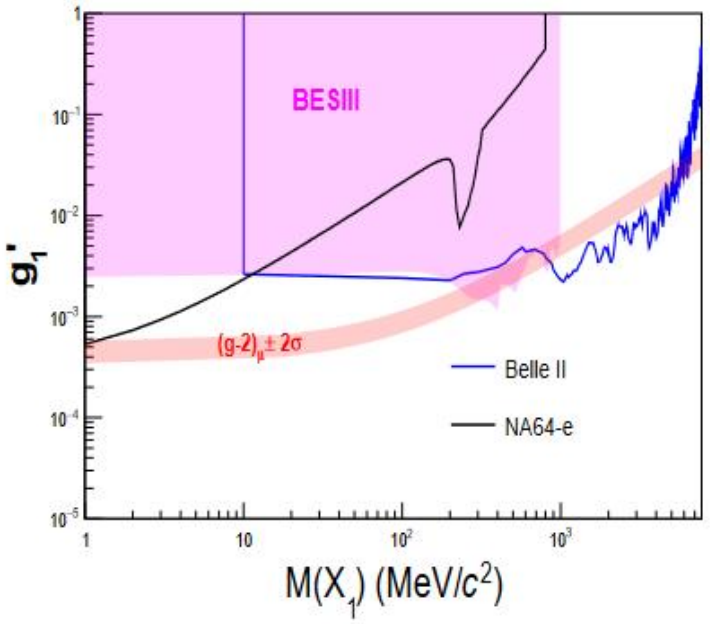
Upper limits on the couplings

PRD (2024) 109, L031102

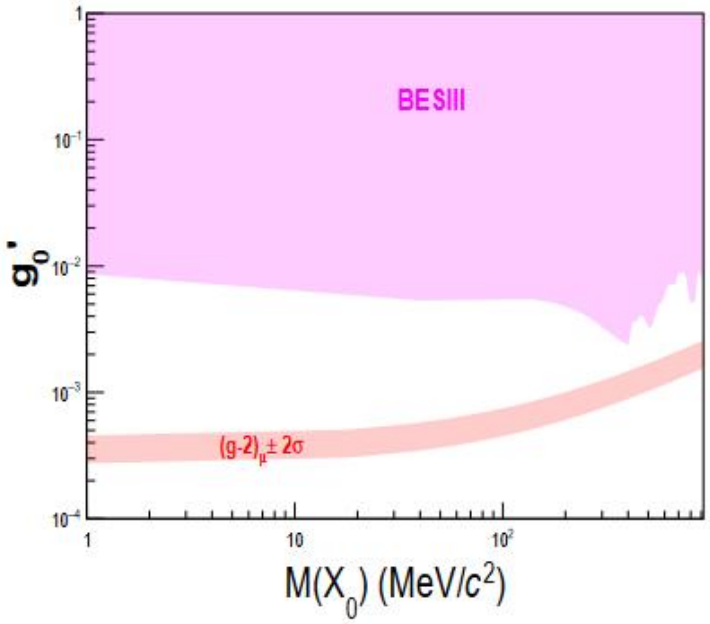
"vanilla" $L_\mu - L_\tau$ model



"invisible" $L_\mu - L_\tau$ model



"scalar" $U(1)$ model



BESIII, BelleII, NA64-e: $X_1 \to \nu\nu$
BABAR, CMS, Belle: $X_1 \to \mu^+\mu^-$

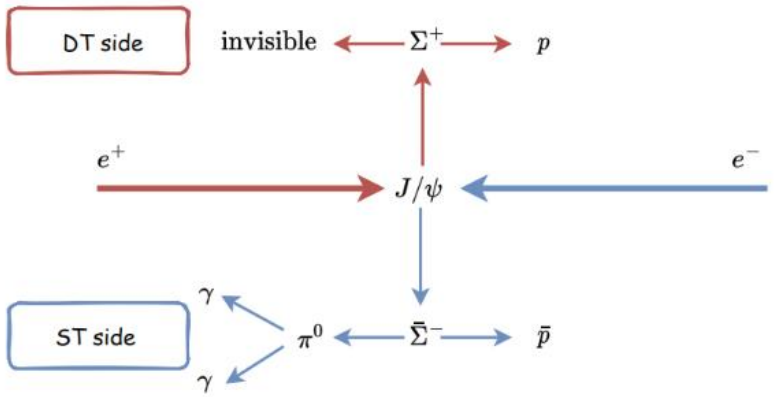
BESIII provides best sensitivity in 200-860 MeV/c^2

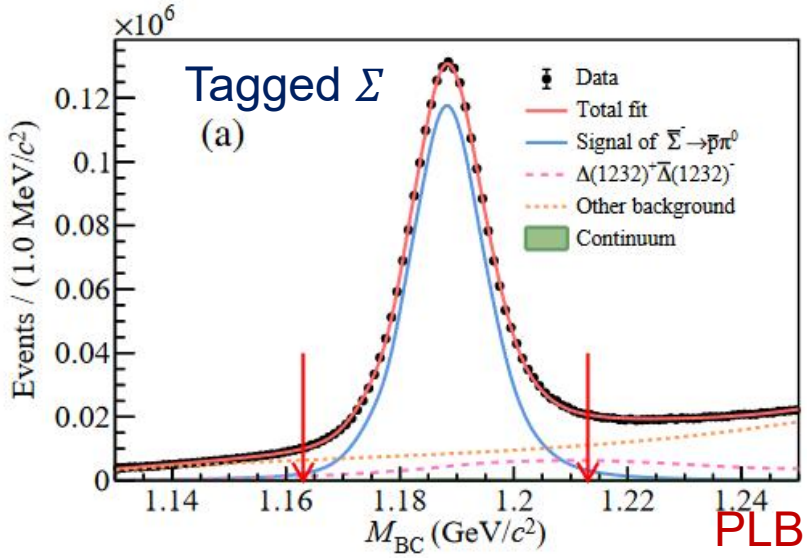
BESIII perform the first direct search for the scalar

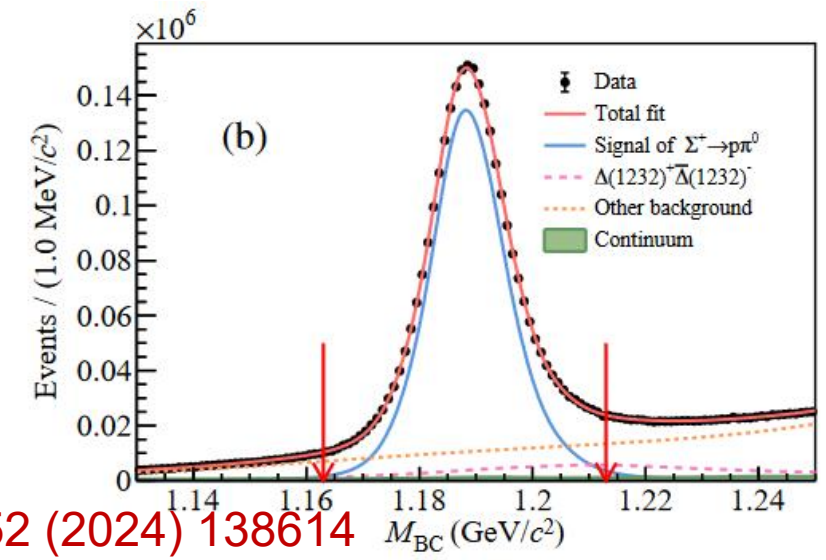
Search for $\Sigma^+ \rightarrow$proton+invisible

- Multiple new physics effects can enter the signal decay
  - FCNC process $s \rightarrow d\nu\nu$
  - Massless dark photon, QCD axion...
- 10 million pairs of $\Sigma^+\bar{\Sigma}^-$ are produced

  (10 billion J/ψ decays)
- Enables studies of decays with “missing” particles by tagging one $\Sigma \rightarrow p\pi$



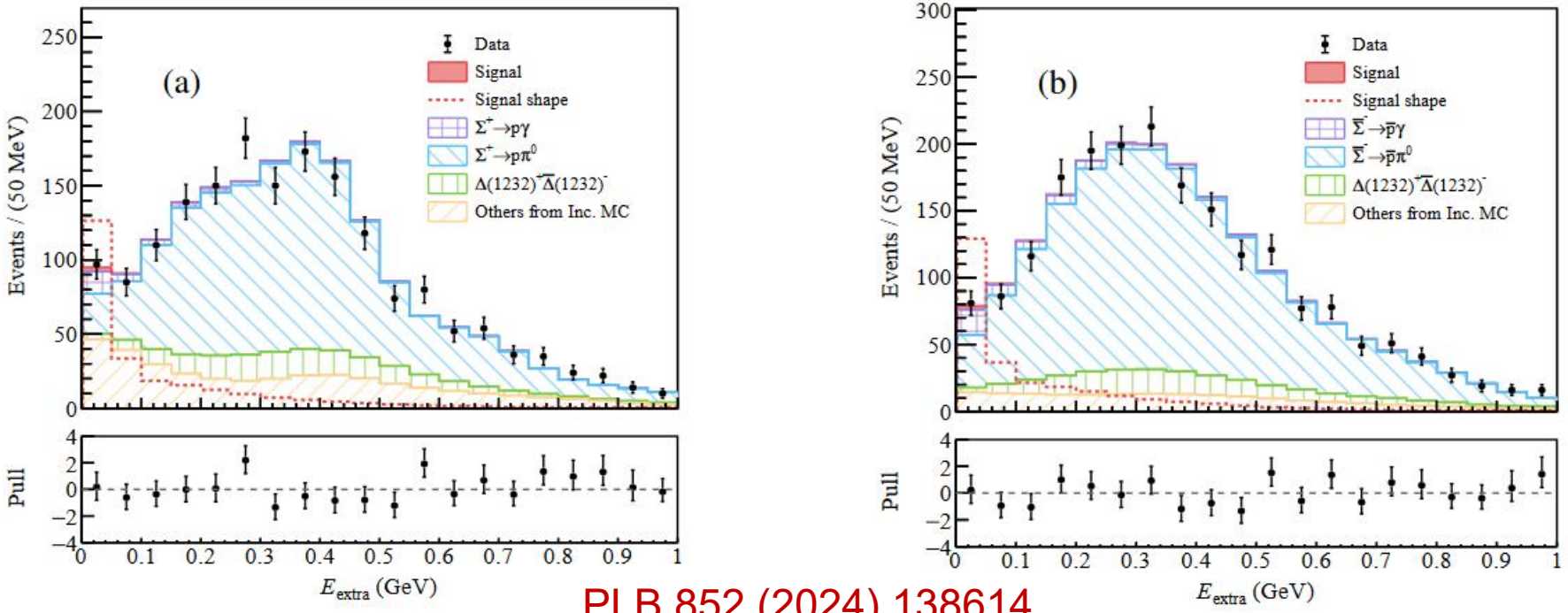




PLB 852 (2024) 138614

Search for $\Sigma^+ \to$proton+invisible

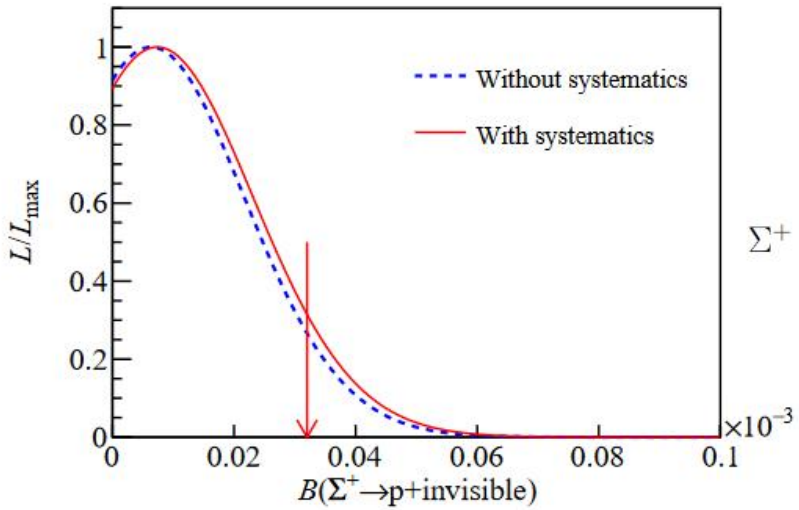
- Count the energy deposit in electro-magnetic calorimeter
- A unique method at electron-positron colliders

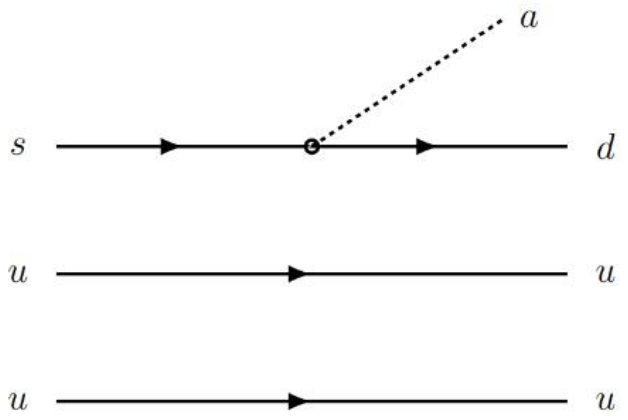


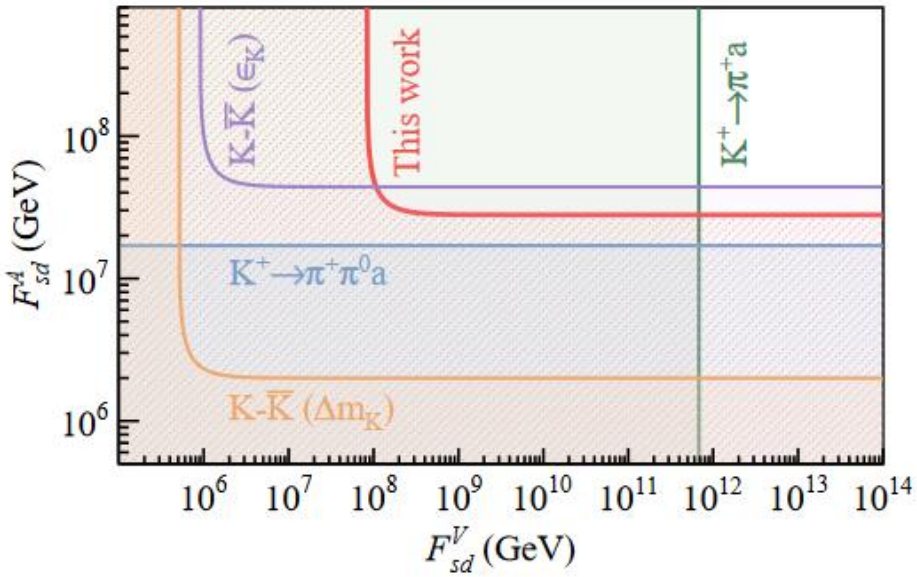
PLB 852 (2024) 138614

- Anti-protons are more likely to interact with detector materials, causing the energy deposit larger than proton
- Requires data-driven method to model the background

Search for $\Sigma^+ \rightarrow$proton+invisible







PLB 852 (2024) 138614

$$\Gamma(\Sigma^+ \rightarrow pa) = \frac{M_{\Sigma^+}^3}{16\pi}\left(1-\frac{M_p^2}{M_{\Sigma^+}^2}\right)^3 \left(\frac{(-1)^2}{|F_{sd}^V|^2}+\frac{0.34^2}{|F_{sd}^A|^2}\right)$$

PRD 102 (2020) 015023

- First upper limit of the decay branching fraction is reported ($< 3.2 \times 10^{-5}$ at 90% CL.)
- Complementes other searches for the QCD axion with tiny mass (<1 eV) and long lifetime (PLB 169 (1986) 73), also constraints massless dark photon models

Search for an axion-like particle

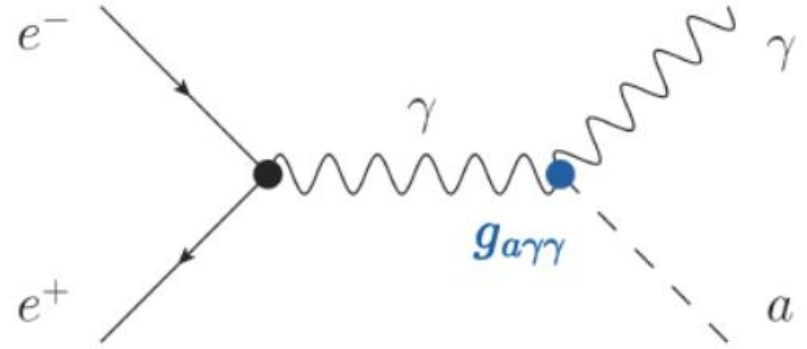
- An axion-like particle (ALP)
  - is a pseudo-scalar particle
  - introduced by the spontaneous breaking of Peccei-Quinn symmetry to solve the strong CP problem of the QCD

    Phys. Rev. Lett. 40, 223 (1978); Phys. Rev. Lett. 40, 279 (1978)

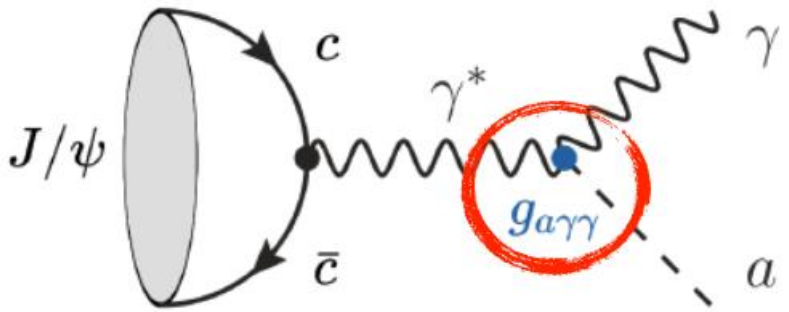
    Phys. Rev. Lett. 38, 1440 (1977); Phys. Rev. D 16, 1791 (1977)
  - **predicted by many models beyond the SM and proposed to be a cold DM candidate**
  - **couples to a pair of photons with ALP-photon coupling $g_{a\gamma\gamma}$**
  - **experimental bounds on $g_{a\gamma\gamma}$ with m_a range of MeV/c^2-GeV/c^2, mainly constrained by e^+e^- colliders**

    Phys. Lett. B 753, 482 (2016)

ALP-Strahlung process



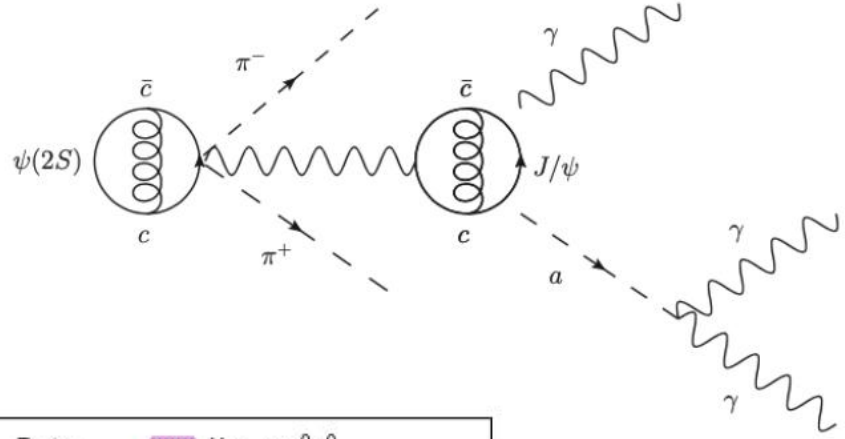
Radiative decay

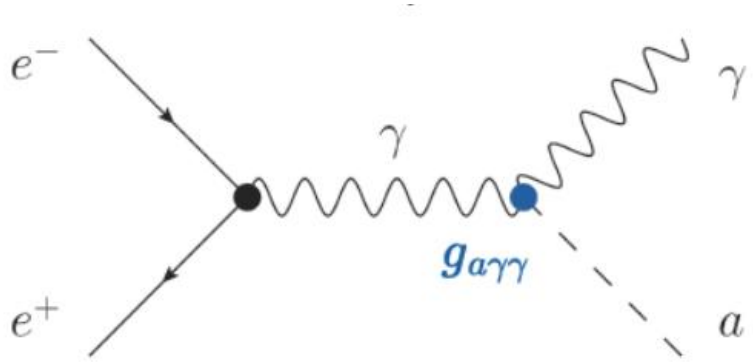


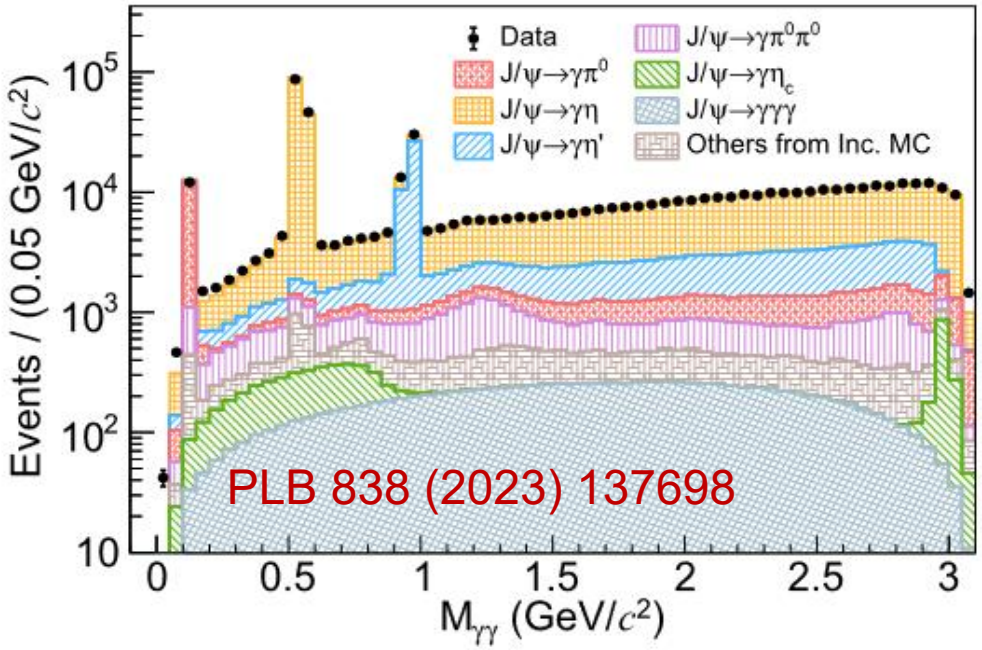
JHEP 06 (2019) 091

Search for ALP with $\psi(2S)$ data

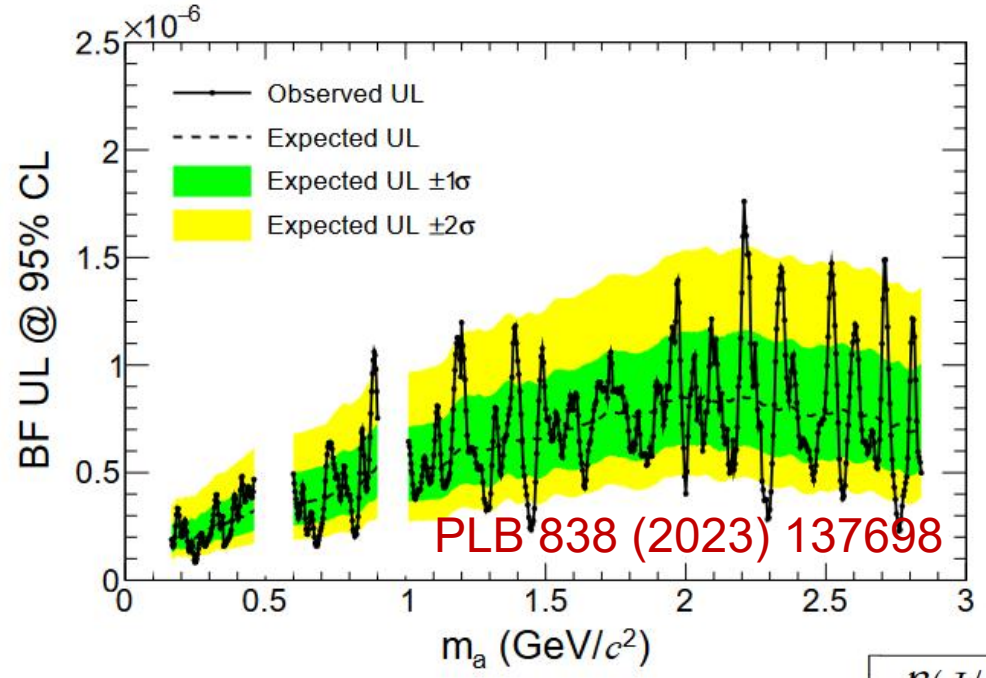
- Using 2.7 billion $\psi(2S)$ data, BESIII has set one of the best limits on $g_{a\gamma\gamma}$ via $J/\psi \to \gamma a(\to \gamma\gamma)$
- Can avoid the pollution of non-resonant production and QED background

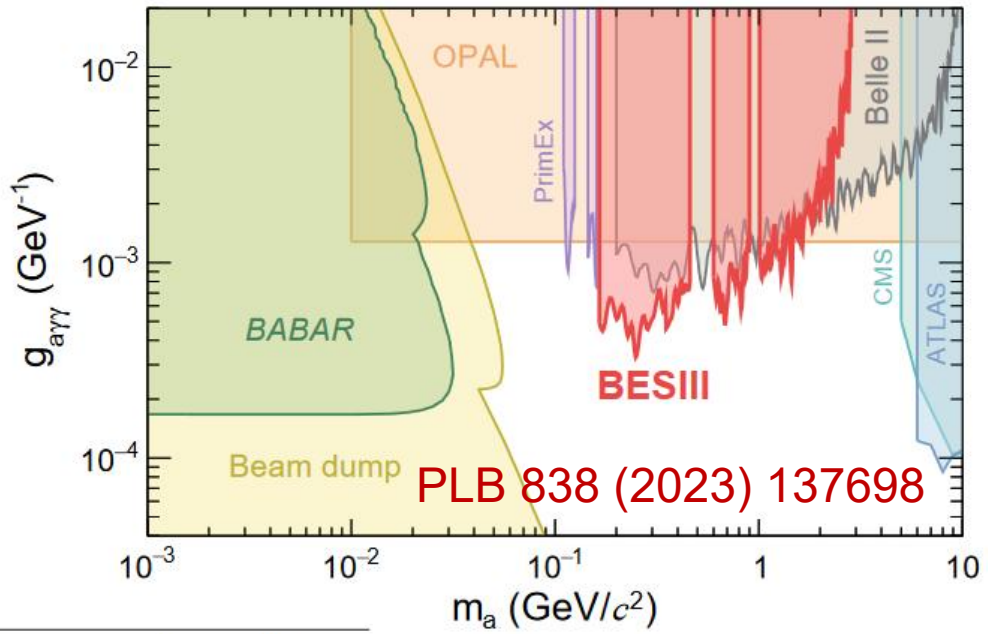






Search for ALP with $\psi(2S)$ data



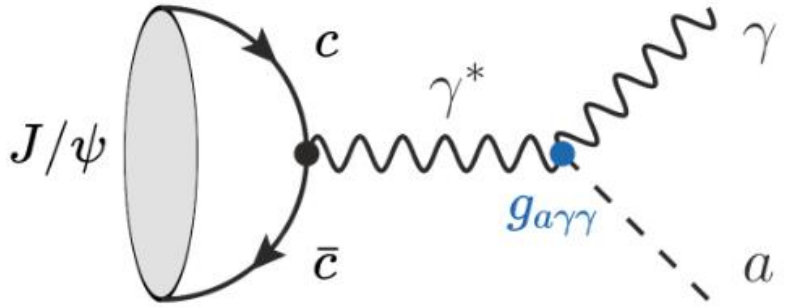


$$g_{a\gamma\gamma} = \sqrt{\frac{\mathcal{B}(J/\psi \to \gamma a)}{\mathcal{B}(J/\psi \to e^+e^-)}(1-\frac{m_a^2}{m_{J/\psi}^2})^{-3}\frac{32\pi\alpha_{\rm em}}{m_{J/\psi}^2}}$$

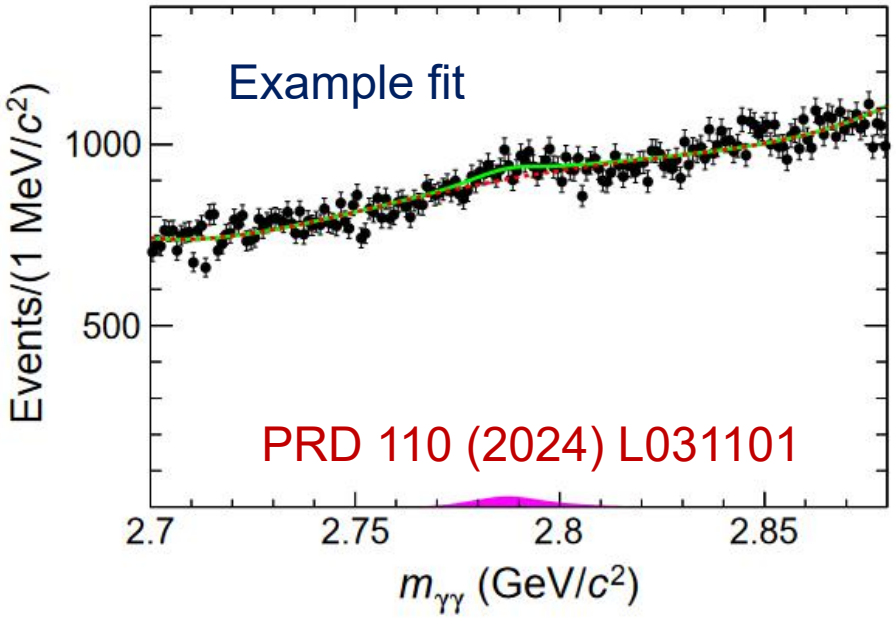
- Limits at $10^{-6} - 10^{-8}/\mathrm{GeV}$ level
- Most stringent constraints on $g_{a\gamma\gamma}$ in the m_a range [0.165, 1.468] GeV/c^2 up-to-date
- Can be further improved with 10 billion of BESIII J/ψ data, which can include both radiative $\mathrm{J}/\psi \to \gamma a$ and ALP-strahlung process $e^+e^- \to \gamma a$

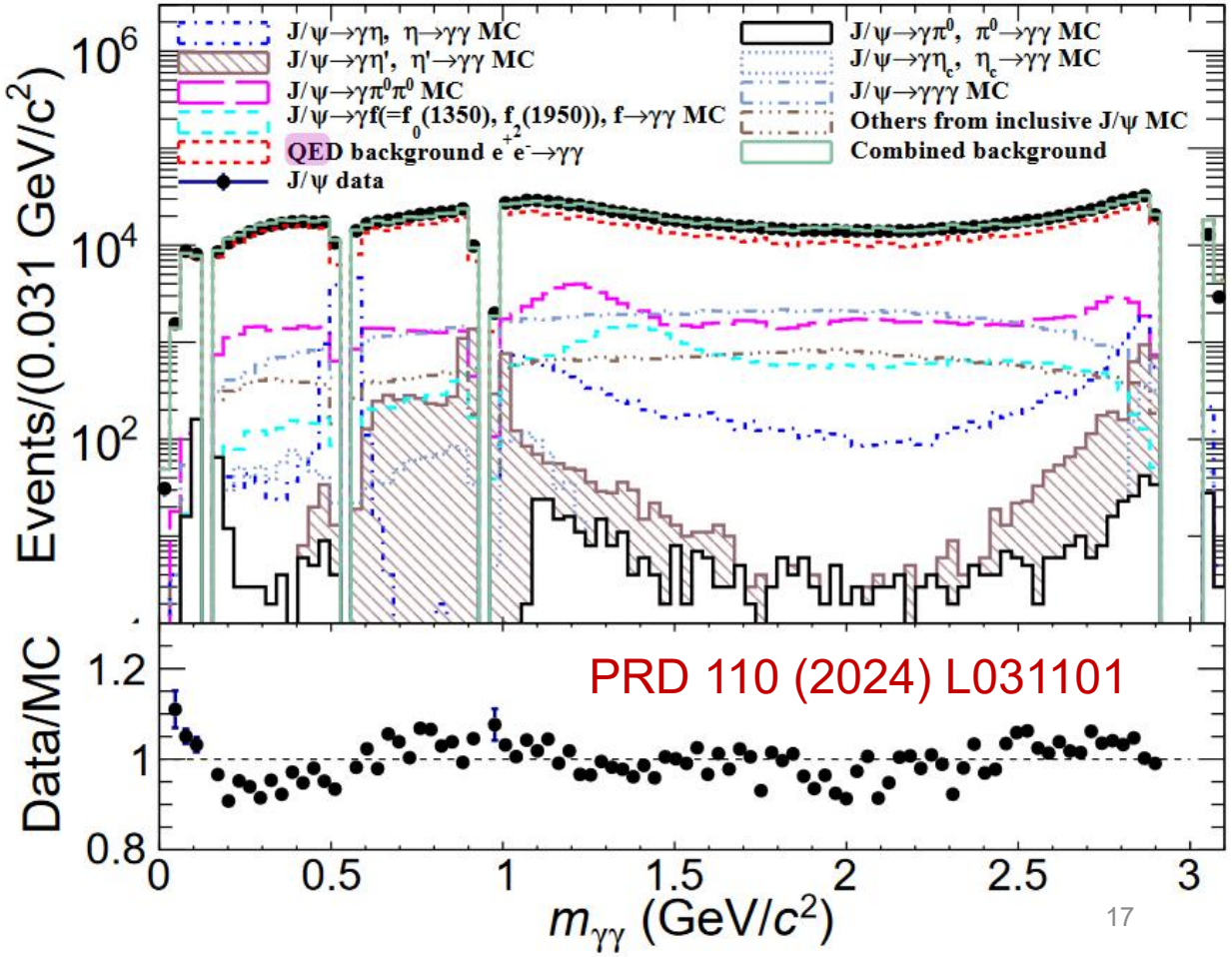
  Expected pollution of ALP-strahlung process $e^+e^- \to \gamma a$ in $\mathrm{J}/\psi \to \gamma a$

Search for ALP with J/ψ data

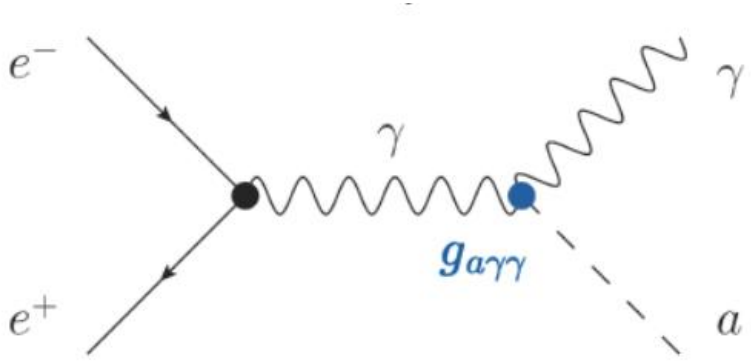


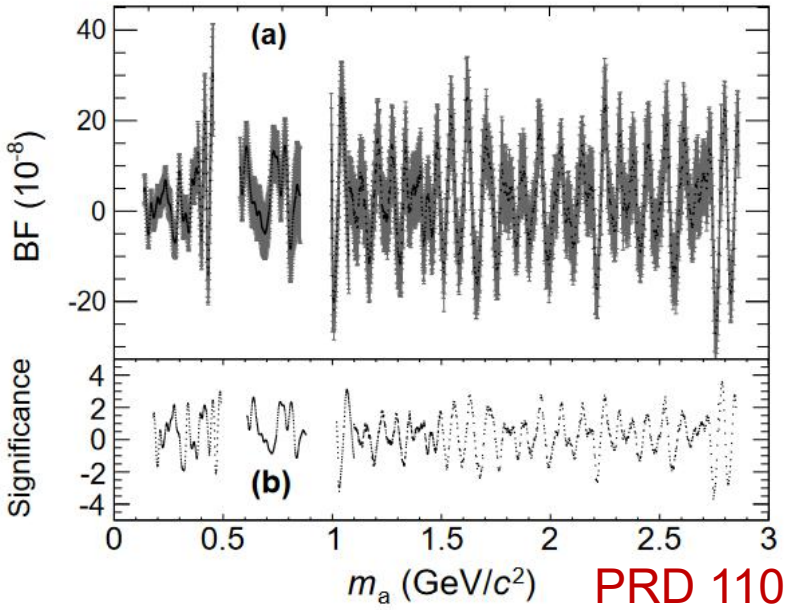
- Using 10 billion J/ψ data, BESIII has the best limits on $g_{a\gamma\gamma}$ via $J/\psi \to \gamma a(\to \gamma\gamma)$
- Huge but flat QED background (estimated with continuum data), found to have minimal effect on signal





Search for ALP with J/ψ data





PRD 110 (2024) L031101

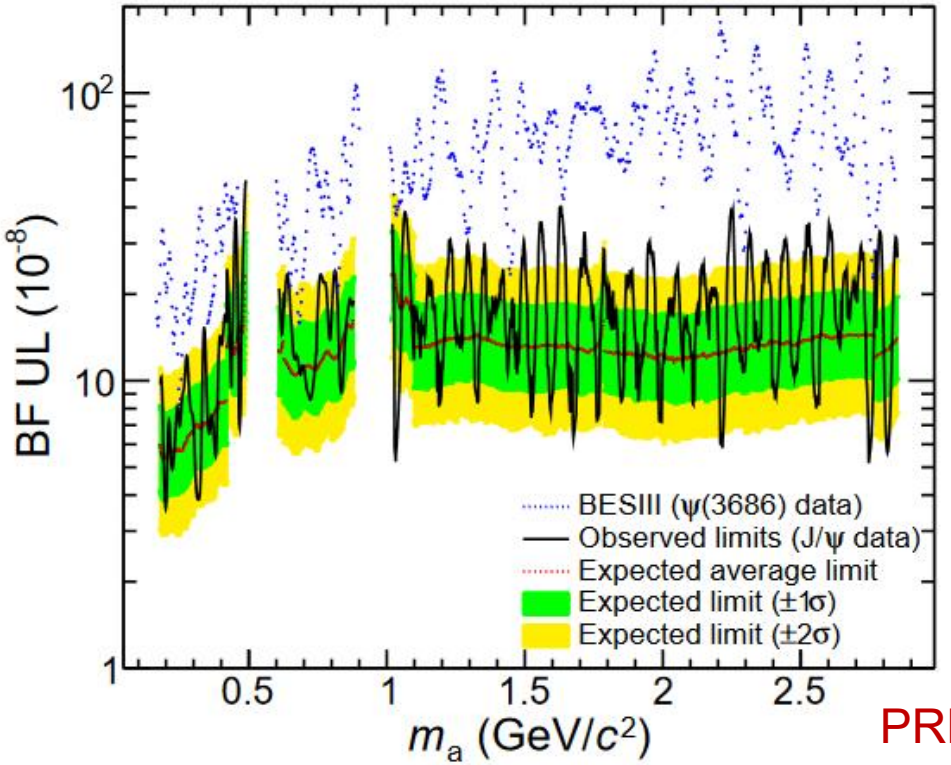
- **Background of ALP-Strahlung process is estimated with $\sigma_a^{rad} = \frac{N_{J/\psi}}{L_{J/\psi}} . \mathcal{B}(J/\psi \to \gamma a)$ and taken as a systematic uncertainty of 4.4%**

- Uncertainty associated with the fit model is estimated by varying the paraterized PDFs of signal and background, which is 9.2%

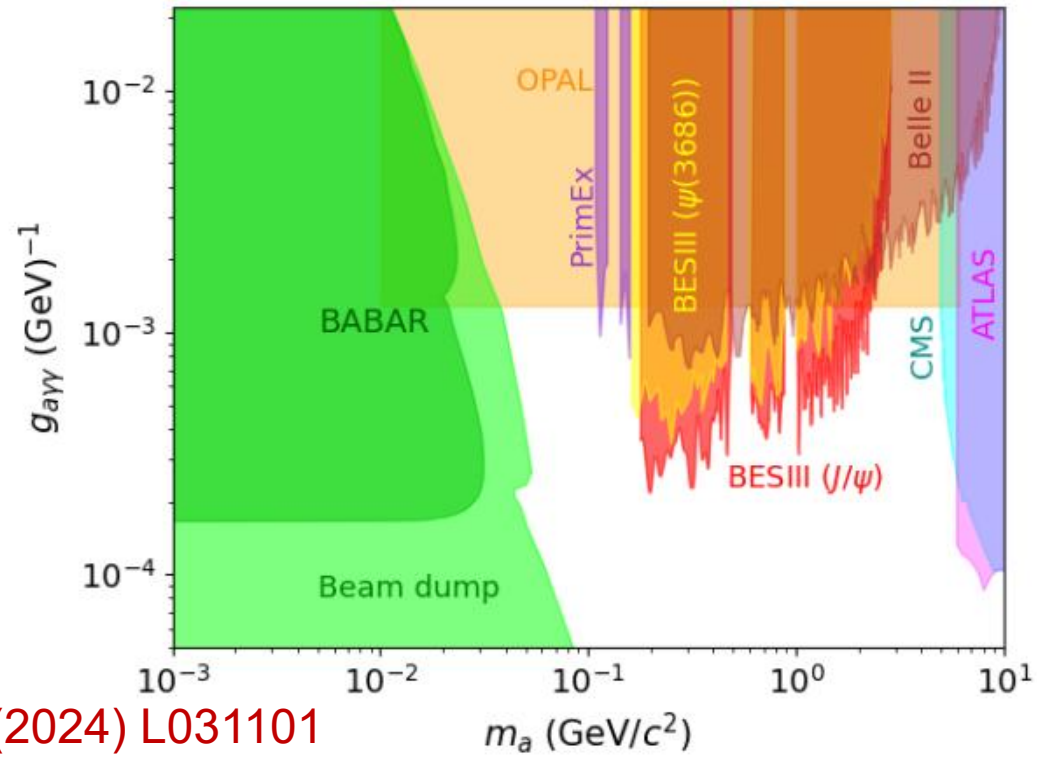
- At a given mass point $m_a = 2.786\ \mathrm{GeV}/c^2$, the global significance is 1.6sigma→no significant signal has been found

Search for ALP with J/ψ data

95% Confidence level ULs on product branching fraction



95% Confidence level ULs on ALP-photon coupling

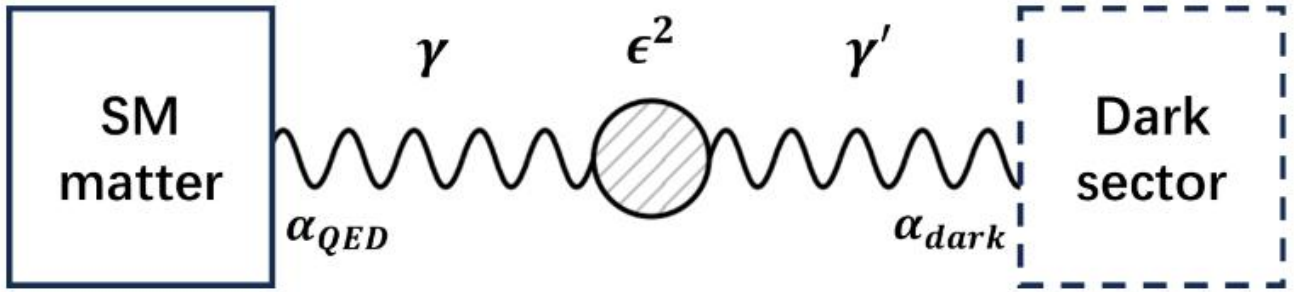


PRD 110 (2024) L031101

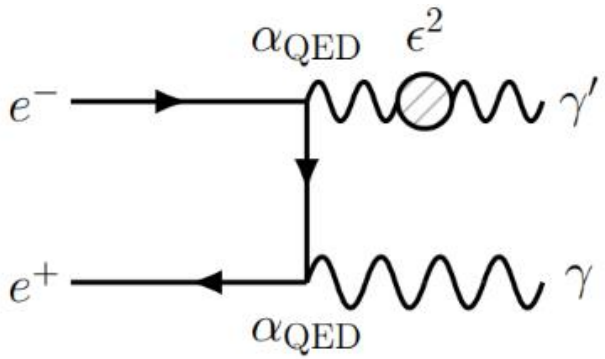
These results supersedes the previous BESIII (Belle-II) search by 3 (5) times
Phys. Lett. B 838, 137678 (2023); Phys. Rev. Lett. 125, 161806 (2020)

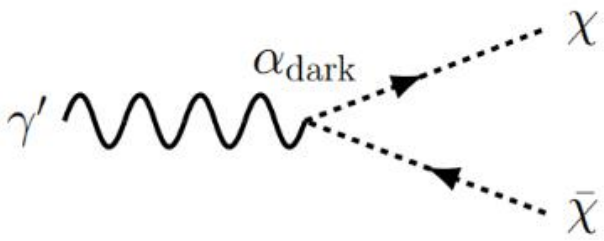
Search for massive dark photon

- Extra gauge group $U(1)_D$
  - The associated gauge boson is the dark photon
  - Massive if the symmetry is spontaneously broken
- Dark photon has a kinetic mixing with the SM photon $\frac{1}{2}\varepsilon F'_{\mu\upsilon}F^{\mu\nu}$
- Effective coupling strength with SM matter $e\varepsilon$
- Can be produced in any process by replacing the SM photon

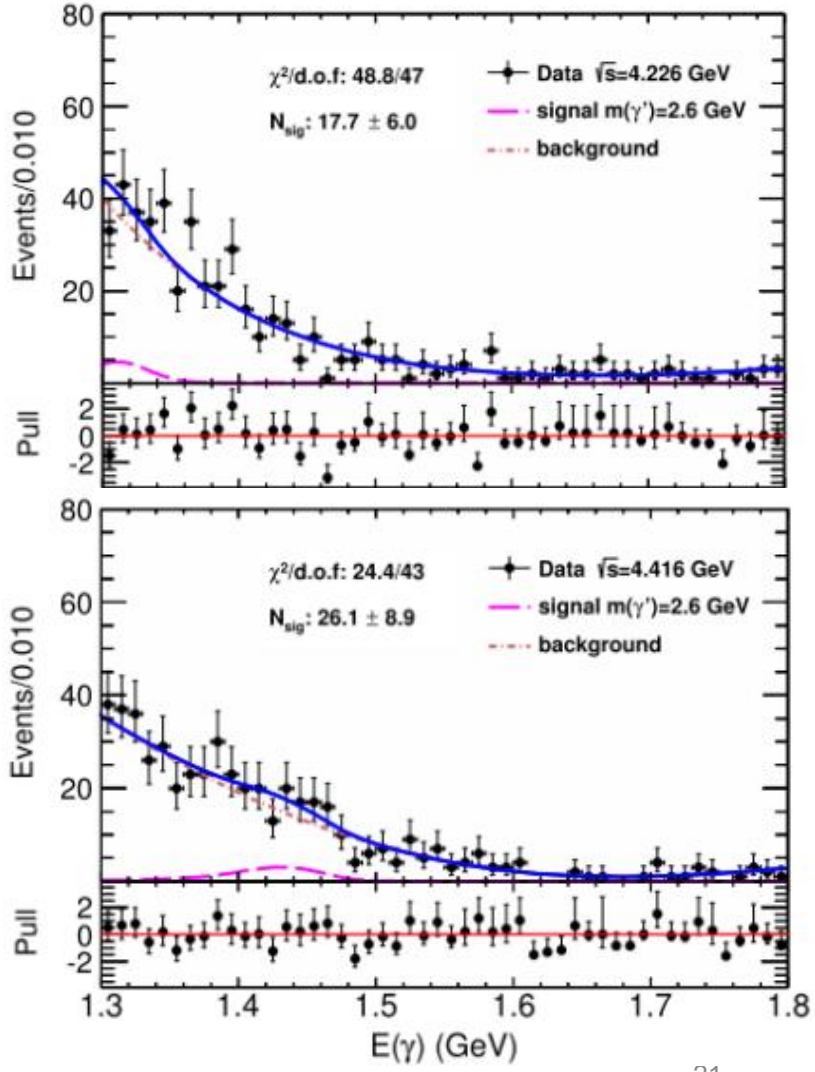


Search for massive dark photon in $e^+e^- \to \gamma\gamma'$





- γ' predominantly decays to $\chi\bar{\chi}$ if $m_\chi < m_{\gamma'}/2$
- Search for a peak in the SM γ energy spectrum $E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}}$
- $14.9\ \text{fb}^{-1}$ data samples between $\sqrt{s}$=4.13-4.60 GeV
- Scan of $m_{\gamma'}$ in [1.5, 2.9] GeV
- Maximum global significance is 2.2σ



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Constraint on mixing parameter ε

$$\sigma(e^+e^- \to \gamma\gamma') = \frac{2\pi\alpha^2}{s}\epsilon^2\left(1-\frac{m_{\gamma'}^2}{s}\right)\times\left(\left(1+\frac{2\frac{m_{\gamma'}^2}{s}}{\left(1-\frac{m_{\gamma'}^2}{s}\right)^2}\right)\log\frac{(1+\cos\theta_c)^2}{(1+\cos\theta_c)^2}-2\cos\theta_c\right)$$

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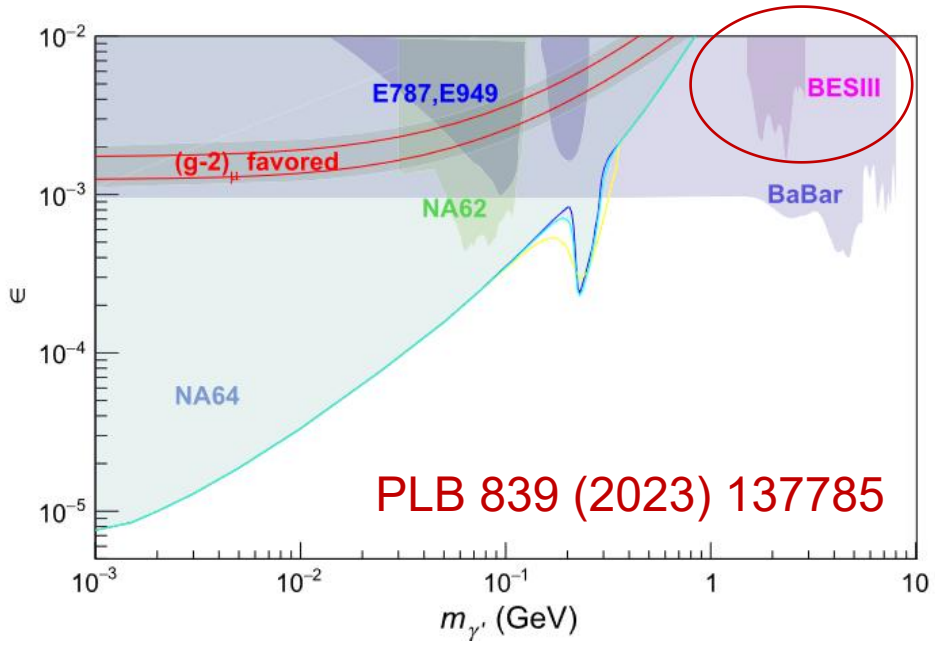
$\cos\theta_C$ is the cut on γ polar angle



BESIII will produce more competitive constraints with 20 fb^{-1} data at 3.773 GeV and other points

Summary

- BESIII has a good potential to search for BSM physics with a clean collision enviroment, is especially ideal for decays with neutral and "missing" particles
- The searches performed so far have significantly constrained the allowed phase space of theoretical models
  - Muonphilic particles, ALPs…
- More results will come soon by analysing the 10 billion J/ψ, 2.7 billion $\psi(3686)$ and 20 fb^{-1} $\psi(3770)$ decays

Thanks!